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SPECIAL FEATURES OF STRUCTURE FORMATION DURING ROLLING STRIPS IN THE HELICAL ROLLS AND LONGITUDINAL WEDGE MILL

Abstract. In this paper, a new technology for the production of sheet products with an ultrafine-grained structureis presented. The ultrafine-grained structure is obtained by applying an intense plastic deformation, developed by the screw-like rolls. In thework the stress-strain state (SSS) of a workpiece at rolling in helical rolls and a longitudinal-wedge mill is investigated. Quantitative datawere yielded by using the finite element method, the ANSYS-LS/DYNA and MSC.SuperForgesoftware and the main regularities of SSS and temperature distribution during rolling blanks in helical rolls with a different number of passes and on a longitudinal-wedge millare established. A rational technology for rolling brass L63 was developed and tested under the laboratory conditions. Particular attention is paid to the analysis of the effect of rolling regimes in helical-shaped rolls and longitudinal-wedge mill on the formation of an ultrafine-grained structure in brass L63. It is established that rolling in screw-like rolls and longitudinal-wedge-shaped mill of brass L63 leads to an increase in the strength and plastic properties of sheet metal.

Key words: brass L63, ultrafine-grained structure, rolling, stress-strain state, numerical modeling, intensity of stresses and deformations, strength, plasticity.

Introduction. Creation of metals and alloys with ultrafine-grained(UFG) structure, i.e. having grain size in submicrocrystalline (grain size in the range of 100-1000 nm) or nanocrystalline (less than 100 nm) ranges is an actual task of modern materials science [1-4]. This is due to the unique physical and mechanical properties and the possibility of wide practical use of such materials. Properties of UFG materials and their behavior usually differ significantly from both the characteristics of large-crystal materials and the properties of materials subjected to conventional deformation processing (rolling, drawing, etc.). For example, it was shown in [5, 6] that UFG materials can have unusual mechanical properties, very high strength and ductility, considerable fatigue and viscosity, increased diffusion properties and the ability to form, as well as improved magnetic properties and a number of other attractive functional and structural properties.

In recent years, methods of intensive plastic deformation (IPD), such as torsion under hydrostatic pressure (THP), equal-channel angular pressing (ECAP), multi-axis deformation, screw extrusion, accumulated rolling with compound and others, which are based on the application of large shear strains under high pressure and low homological temperatures [7, 8].

However, samples after many methods of IPD have small dimensions, for example, after THP samples are obtained in the form of discs with a thickness of less than 1 mm and a diameter of up to 20 mm, and after ECAP - volume billets in the form of cylinders up to 50 mm in diameter and up to 200 mm in length. Therefore, the IPD methods have been further developed, the ECAP methods withcounterpressure, continuous ECA pressing, etc. have been developed, which make it possible to obtain rod samples with a UFG or a dimensionally different structure with different sizes [9, 10].

It should be noted that the above-described IPD methods make it difficult to produce sheet metal with an ultrafine-grained or nanogranular structure.

According to the authors of [11], sheet rolling with an ultrafine-grained structure can be obtained by various technological and constructive methods: the use of blanks and rolls with a wavy or corrugated surface, asymmetric rolling, uneven setting of the rolling in its thickness and width, the use of crossed rolls, and rolls with a ledge on the surface, etc. The authors of [11] note that in all these cases, intense macro-shear is achieved as a result of a local deformation effect on the rolled metal.

The Japanese firm JFE Steel proposed a method for multiple consecutive alternating bending of the steel strip after hot rolling (the method of deformation accumulation by bending) [12]. It can be seen from the materials of the work that, in contrast to conventional rolling, the use of alternating bending makes it possible to roll a sheet blank without changing its thickness. Therefore, this method allows the blank to be deformed by cyclic bending unlimited number of times. This makes it possible to obtain hot-rolled strips with an ultrafine-grained structure. According to the authors of [12], this method of rolling can be used in industry to improve the quality of rolled metal. This is due to the fact that rolling by cyclic bending led to the production of hot-rolled strips with a grain size of ferrite of 1 μm or less.

Thus, many new designs of rolls have been proposed to improve the quality of sheet metal. However, many rolls have not found their wide application in production for the following reasons: the complexity of their manufacture; the difficulty of installing them on rolling mills.

It is important to note that for the production of strips with nanocrystalline structure from known IPD methods, foil rolling has been widely used in practice. However, due to the small size of the foil, it is of little use for subsequent shaping operations.

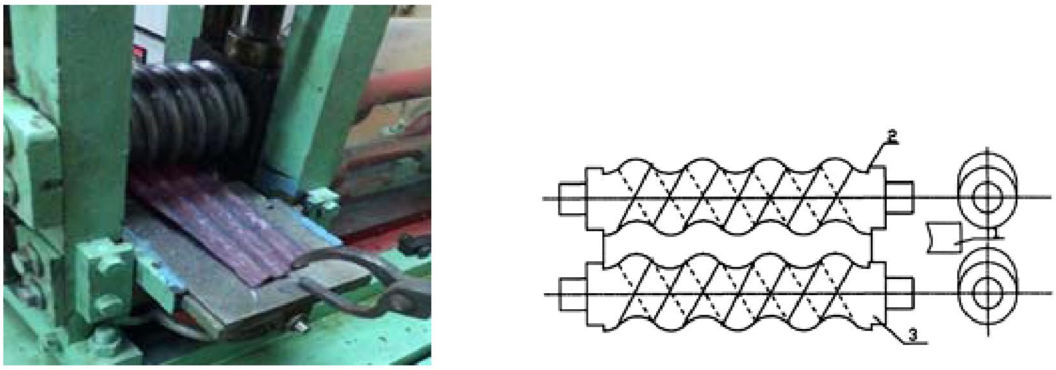
In connection with the foregoing, the development of new IPD methods that make it possible to produce sheet metal with an ultrafine-grained or nanogranular structure is an urgent task.

Numerous studies show that the use of the IPD method can significantly grind the microstructure and, as a result, increase the strength of the metals and alloys. However, an increase in the strength of metallic materials usually leads to a decrease in their ductility. Achieving the high strength and plasticity, required to create new promising structural and functional materials, is one of the fundamental problems in materials science. In the case of UFG metals and alloys, this problem can be solved by controlling their microstructure. The fact is that the structure of materials subjected to the IPD is very complex and is characterized not only by the presence of ultra-fine grains, but also by their shape and distribution, the special structure of the boundaries, high dislocation density and other parameters. The formation of such a structure, determining the level of mechanical properties of metals and alloys, essentially depends on the treatment modes and, first of all, on the values of the applied pressure, the degree of deformation, and the temperature. In addition, the microstructure and, accordingly, the properties of metals, of course, also depend on the combination of different IPD schemes and subsequent annealing.

Recently, much attention has been paid to the study of the structure and properties of copper alloys after the IPD for the purpose of using them in the electrical industry. But practically all works were devoted to equal-channel angular pressing (ECAP) of copper alloys [13-22], and only a few - to torsion under hydrostatic pressure (THP) [23-25]. ECAP makes it possible to obtain relatively large bar stock with a submicrocrystalline structure. However, it is not possible to obtain sheet materials with a UFG structure

Therefore, the implementation of new opportunities and the development of IPD methods for producing strips of metals and alloys with a UFG structure and increased mechanical properties is very relevant, and is of scientific and practical interest and is the subject of this work.

Equipment, materials and the method of the experiment. In [26] a tool with rolls, which have screw working surfaces, was developed (figure 1). This tool is designed to produce semi-finished products with a fine-grained structure. The developed tool implements the IPD without significant changes in the initial shape and dimensions of the workpiece. It should be noted that for rolling thin strips from a workpiece with a fine-grained structure, a multifunctional longitudinal-wedge mill (LWM) of a new design was used (figure 2) [27].

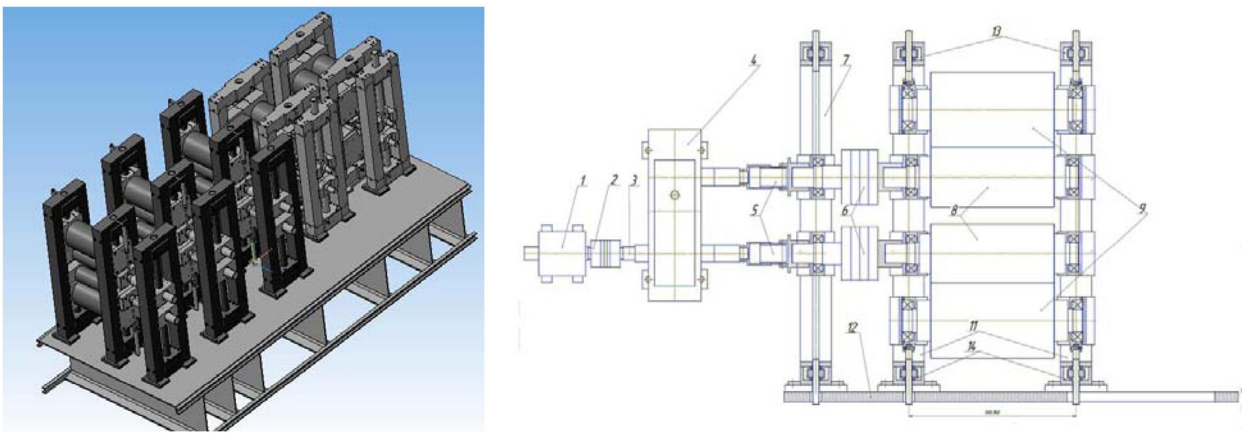


a b

a – mill; *b* – scheme of rolling

Figure 1 – Rolling mill DUO with screw rolls: 1 - billet; 2 - the upper roll; 3 - lower roll

The multifunctional LWM contains working stands, an electric motor, a coupling, supporting non-driven rolls, working drive rollers, a frame, a base plate. The cage drive motors, which are provided by the AC motor, contain working and supporting rolls of constant diameter, and in successive cages the diameter of the working rolls decreases, and the diameter of the supporting rolls increases in the rolling direction. In this case, the rolls are rotated through an individual coupling, reducer, gear wheel and spindles.



a b

Figure 2 – Multifunctional LWM (*a*) and the structure of its working stands (*b*):
1 - motor-reducer; 2 - coupling; 3 - shaft; 4 - pinion cage; 5 and 6 - spindles; 7 - bearing cage;
8 - working rolls (D_{P1} = 180 mm, D_{P2}=150 mm, D_{P3} = 125 mm, D_{P4} = 106 mm, D_{P5} = 94 mm);
9 - supporting rolls (D_{OP} = 220 mm); 11 - stand; 12 - base plate; 13 and 14 - pressure mechanisms

Tool for hot rolling of steel and alloys, contains upper and lower rolls with screw working surfaces. In this case, the protrusions and hollows of the upper roll are made along the helical lines opposite to the depressions and protrusions of the lower roll. It should be noted that the protrusions and valleys of the upper and lower rolls have the same width and, correspondingly, height or depth.

When rolling the workpiece in this tool, the protrusions of the working surface on one side of the rolls are opposite to the valleys of the working surface on the other side of the rolls. Rolling in the first and subsequent pass is carried out with a single reduction $\varepsilon = \Delta h_B / H_o$ and $\varepsilon = 2\Delta h_B / H_o$ (where Δh is the height of the protrusion or the depth of the hollow of the undulating working surface; H_o – the height of the workpiece before rolling), respectively. Such rolling provides an effective grinding of the metal structure of the billet by developing an alternating bending deformation in the longitudinal and cross sections of the billet.

For the development of the technological process, allowing, without disrupting the continuity of the workpiecematerial, to evenly distribute the accumulated deformation, i.e. to obtain a high-quality billet L63, the stress-strain state (SSS) of the billet was examined for rolling in helical rolls (HR) and LWM. The mathematical modeling of the rolling process in the HR and LWM is a complex process, because of the very large number of determining parameters and the ambiguous nature of their influence. The correct formulation of the problem leads to a system of integral-differential equations even for simple rolling cases. It is not possible to solve this problem analytically. The finite element method can be used to solve such problems [28-31].

Studies of SSS of the billet in the rolling process is contact, elastoplastic, nonlinear. When rolling in HR and LWM, there are large displacements, deformations and stresses, as well as a temperature gradient. Therefore, using the «ANSYS-LS/DYNA» and «MSC.SuperForge» software products, a mathematical simulation of the rolling processbythe finite element method was produced [29, 31], i.e.the SSS and the temperature field of the deformed billetwere investigated.

To determine the SSS of the billet during rolling in HR, theANSYS-LS/DYNA software product was used [29]. Simulation began with the construction of a helical tool with a rolled workpiece. The geometry of the helical tool and the rolled workpiecewas built in the CAD system SIEMENSNX6 and subsequently imported into «ANSYS/LS-DYNA».

The required type of the final element was selected from the element's feature library in «ANSYS/LS-DYNA». The literature review has shown that Solid 164 or Shell 163 are usually used as the types of elementin determining the volumetric SSS of metal working with pressure [29]. The final element SHELL 163was selected to simulate the rolled product. This type of element reduces the calculation time and is resistant to the action of large deformations. Shell 163 is a 3 or 4-node three-dimensional shell element, which is able to bend and spring. The element has 12 degrees of freedom in each node.

To determine the SSS of the billets, the rectangular shape samples were used with a size of 6×100×200 mm. The deformation was carried out according to the following mode: heating to a temperature of 700 °C, rolling by four passes in the HR to a thickness of 5.9 mm. When modeling the rolling process in the HR for the workpiece, a hardened transversely anisotropic material – Transverse Anisotropic Material, was used [29]. The Lencford coefficient R was assumed to be equal to unity, that is, the isotropic material was used for the initial billet. An isotropic material model is used to describe elasto-plastic deformations. The strain hardening of the metal in the process of deformation in HRis found from the hardening curves obtained when the specimen is subjected to uniaxial tension. The curve of the model had an elastic and plastic component. A solid material was usedas the material model of theHR.

It should be noted that the deforming HR had a restriction from all displacements. These rollerscan only be rotated in the rolling direction. The initial flat blank did not have a restriction on movement. The angular velocities corresponding to the rolling direction were set for the HR. The movement of the initial workpiece through the gap between the rolls was due to the effect of frictional forces arising during the bending of the workpiece by the protrusions and valleys of the rolls, which fully corresponds to the process being studied.

When Shell element 163 was used, the following contact conditions were adopted: the initial blank – rollingrolls – forming surface-to-surface contact (ASTS). It is known [29] that surface-to-surface contact is used for arbitrarily located bodies that have significant contact areas.

The contact friction between the initial billet and the HRwas taken equal to 0.39, which corresponds to the hot rolling of brass L63 [30].

«ANSYS-LS/DYNA»was launched. The movements U, the components of the strain tensors ε, the strain rate ξ and the stress σ, the strain and stress intensity (equivalent strain and stresses), the temperature distribution by the volume of the workpiece were calculated by the step-by-step method.

Software product – «MSC.SuperForge» was usedto determine the SSS of the billet during rolling in the LWM[31]. Simulation began from the construction of LWM with rolling workpiece. The geometry of the LWM and the rolling billetwas built in the CAD program of Inventor and subsequently imported into «MSC.SuperForge». To create a finite element model of the billet, three-dimensional (3D) elements were used, which are used to model the flow of metal under bulk strain conditions, i.e. 3D element CTETRA (a four-node tetrahedron) was used to model 3D bodies. For the workpiece and tool model 2,600 elements and 3,200 nodes were required.

To study the rolling process in the HR, a rectangular billet with the dimensions of 6×100×200 mm was used. Brass L63 with a deformation temperature range of 750–880 °C and with mechanical properties: elastic modulus 1.16×10^5 MPa, Poisson's ratio 0.364 and density 8.44 g/cm^3,was selected as the billet material. The workpiecewas rolled at a temperature of 650 °C. In modeling, the workpiece material was considered as an isotropic elastoplastic with nonlinear hardening (BISO). At the same time, for modeling the plasticity of the material of the billet, a Johnson-Cook elasticity and plasticity model was chosen.

The contact conditions between the roll surfaces and the surface of the rolled sheet are simulated by the interaction of the surfaces between the rigid roll and the deformable workpiece material. Reflecting the movement of the roll and the deformation of the material during the rolling process, the contact conditions are constantly updated. This makes it possible to simulate the sliding between the rolls and the material of the workpiece to be deformed. Using Coulomb's law, the modeling of contact conditions between the tool and the workpiece was carried out, the coefficient of friction was adopted as 0.39 [30].

After entering all the initial data and technological parameters of the rolling process, the program started calculation. The calculation time of the process was 20 minutes on a Pentium Duo computer with a clock speed of 3.4 GHz and 2 GB RAM.

The «MSC.SuperForge» system automatically performs all calculations. Given the geometric feature of the complex flow of metal, the program generates a grid of elements. At each step of the solution, the grid of elements is automatically rebuilt. This makes it possible to investigate such features of the rolling process as broadening and elongation during deformation, and also to predict the formation of folds and clamps.

«MSC.SuperForge» software was launched and step by step SSS and the temperature field of the workpiece were calculated

According to the developed method, a graph of the limiting plasticity was constructed, and the methodology of [32] was exploredtocalculate the degree of the plasticity resource use (DPRU).

Under laboratory conditions, a series of experiments was carried out. The brass L63 with a size of 6×150×400 mm was chosen as the material of the billet. Rolling in the mill with HR and on the LWMwas carried out according to the following regimes:

- heating to 700 °C, holding for 2 hours, rolling two passes in screw rolls to a thickness of 5.4 mm, heating at 700 °C, holding for 30 minutes, rolling by two passes in HR to a thickness of 5.0 mm, heating at a temperature of 100^{0}C, aging 30 min, rolling on a five-standsLWM to a thickness of 1.5 mm;
- heating to 700 °C, holding for 2 hours, rolling by four passes in HR to a thickness of 5.4 mm, heating at 700 °C, holding for 30 minutes, rolling by four passes in HR to a thickness of 5.0 mm, heating at a temperature of 100^{0}C, aging for 30 minutes, rolling on a five-standsLWM to a thickness of 1.5 mm.
- heating to 700 °C, holding for 2 hours, rolling by six passes in HR to a thickness of 5.4 mm, heating at 700 °C, holding for 30 minutes, rolling by six passes in HR to a thickness of 5.0 mm, heating at a temperature of 100°C, aging for 30 minutes, rolling on a five-standsLWM to a thickness of 1.5 mm.

The metallographic analysis was carried out using an JNCAENERGY dispersive spectrometer (England) mounted on a JEOL electron microprobe analyzer (Geol) at an accelerating voltage of 25 kV. The range of the JEOL device increases from 40 to 40,000 times. Structural features of the deformed samples were also investigatedby using the JEM-2100CX transmission electron microscope (TEM) at accelerating voltages of 200 kV.

Quantitative analysis of the parameters of the defective substructure was carried out by standard methods. The grids for metallographic analysis were prepared according to the traditional method on grinding and polishing circles. To identify the grain, etching was used in a 3% solution of ferric chloride in 10% hydrochloric acid, with an exposure of 15-20 sec. The grain size (D_g, *μm*) was determined by the method of secants (by measuring ~ 300 grains) under the assumption that the grains are spherical, based on the average chord (*X*) value by the formula: $D_g = 4/\pi \cdot X_{mid}$.

The mechanical properties of the samples at room temperature were determined on an Instron 5882. The samples were cut in such a way that the direction of extension coincided with the rolling direction and was located at an angle of 45 and 90 degrees to the rolling direction. The tests were carried out at room temperature on flat specimens with a working length equal to 6 mm and 10 mm and a cross-sectional area of 1.4×3 mm^2.

Before the tensile tests, the samples were subjected to heat treatment (HT) consisting of quenching and subsequent aging. The heating temperature for quenching was 850 °C, holding at this temperature for 2 hours, cooling in oil. Aging was carried out at a temperature of 250 °C for 5 hours.

Results and discussion. Figures 3 and 4 show patterns of stress intensity and deformation distribution in the workpiece during rolling in HR by four passes. The workpiece heating temperature is 700 °C.

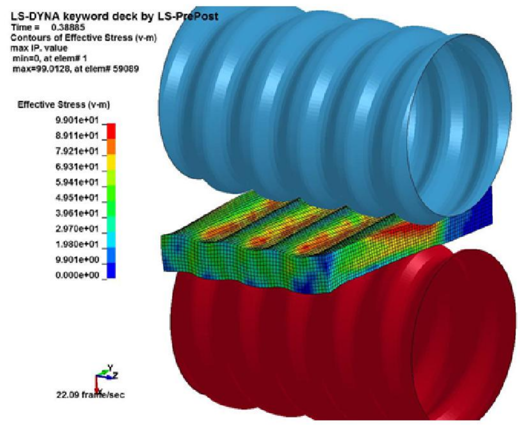
Based on the results of numerical simulation, it is established that:

- at the initial moment of rolling in HR, the intensities of stresses and deformations are localized in the contact zones of the workpiece with the working surfaces of the projections of the rolls;

- an increase in single reduction leads to a shift in the stress intensity and deformation stress from the contact zones to the band zones located under the inclined working surfaces of the protrusions and hollows of the rolls (figures 3 and 4);

- in the process of rolling in HR, the contact zone of the tool with the strip is cooled, while in the areas of action of bending deformation the temperature rises;

- in the second, third and fourth passes of rolling in the HR, the values of stress and deformation intensities increase under the arc-shaped portions of the protrusions and valleys of the rolls;



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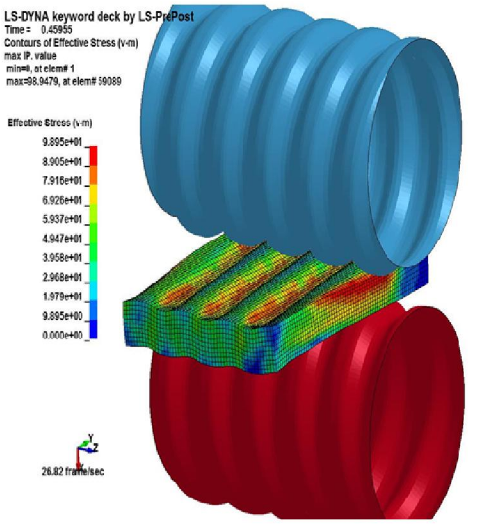

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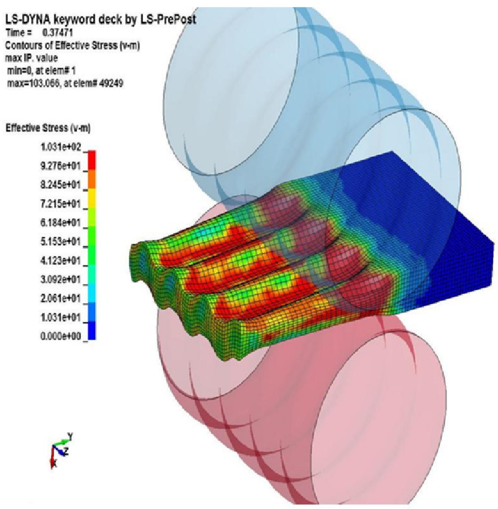

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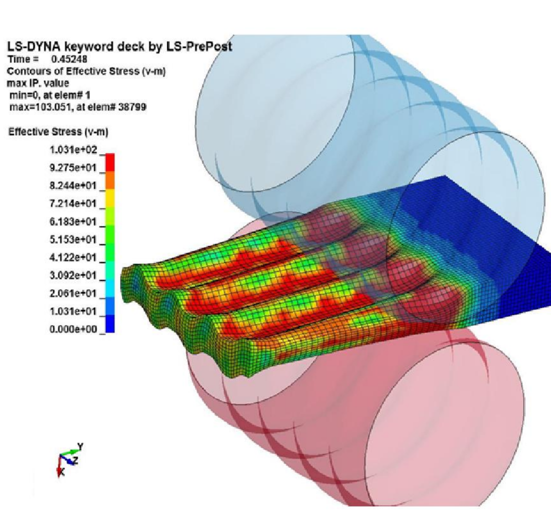
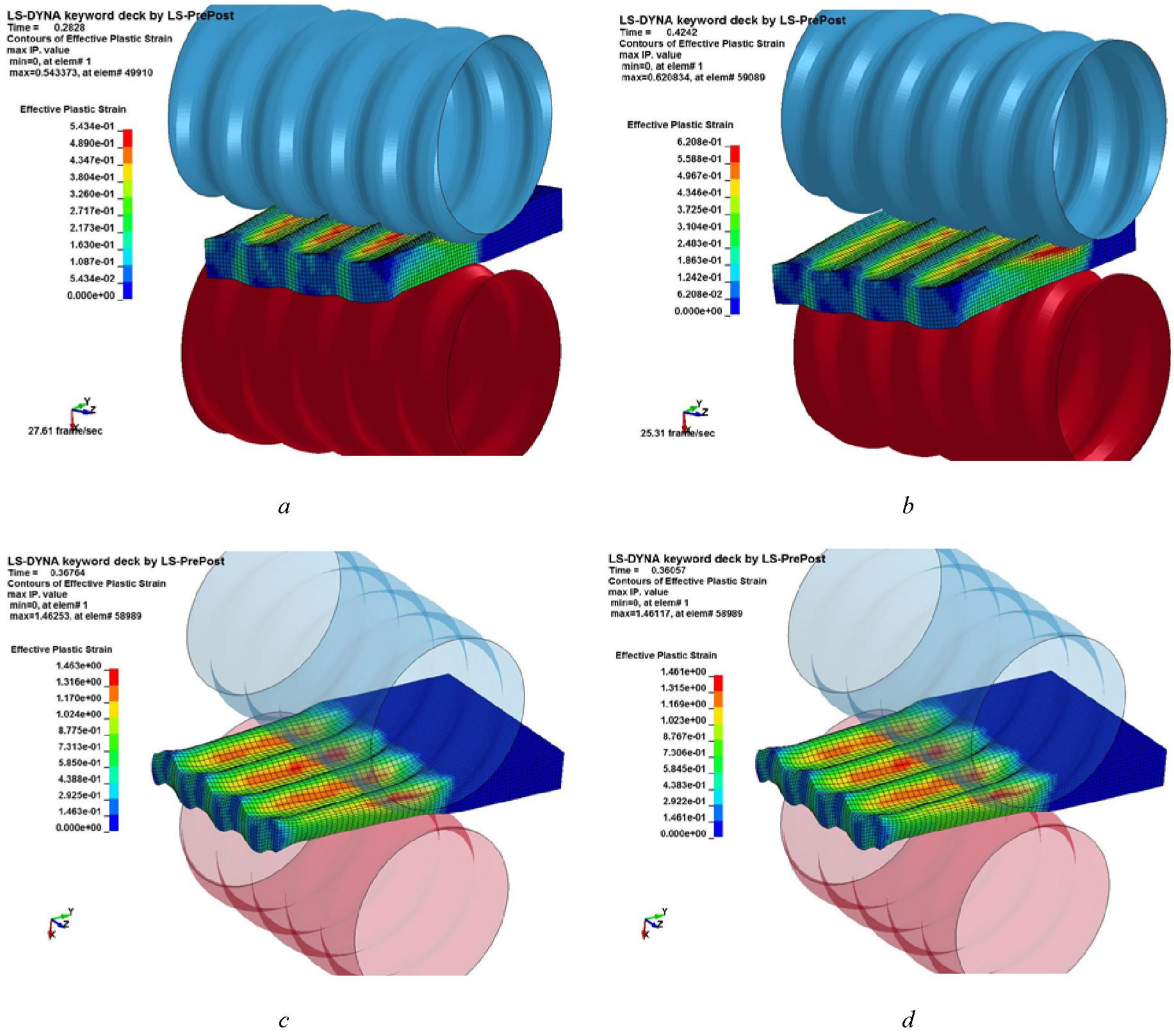


d

Figure 3 – The pattern of stress intensity distribution in the workpiece during rolling in HR (rolling temperature 700 °C):
a – firstpass; *b* – secondpass; *c* – third pass; *d* – fourth pass



a – firstpass; *b* – secondpass; *c* – third pass; *d* – fourth pass

Figure 4 – The picture of the distribution of the deformation intensity in the workpiece during rolling in the HR (rolling temperature 700 °C)

- rolling in the proposed tool, having the same dimensions of the protrusions and valleys of the working surface of the rolls, as well as the protrusions or hollows of the upper roll located opposite to the troughs and projections of the lower roll, respectively, with the aforementioned single reductions, allows the billet of small thickness to be deformed multiple times without changing its dimensions;
- the developed method for rolling a strip in HR ensures an intensive alternating deformation of the strip. The maximum possible shift is realized with a ratio of the width of the protrusion to the width of the cavity equal to 0.8 ... 0.9;
- multiple bending allows to increase the value of the degree of shear deformation. All this makes it possible to achieve an effective grinding of the structure of the alloys, i.e. improve the quality of the sheets;
- the use of a small thickness blank and alternating bending deformation lead to an increase in productivity and a reduction in the laboriousness of the produced sheets, while the energy-strength parameters of the processdecrease;
- when rolling in rolls with screw working surfaces, the projections and valleys formed during rolling are shifted along the width of the rolled strip, which creates additional macroswings along the section of the workpiece and promotes an increase in the intensity of deformation;
- the increase in the intensity of deformation in the case of rolling in rolls with screw working surfaces is twice as high as when rolling in cylindrical rolls;

- an increase in the deformation intensity will lead to the formation of an equiaxial homogeneous fine-grained structure along the section of the strip.

Figures 5 and 6 show the distribution of the stress intensity and deformation during rolling strips in the LWM. The temperature of workpiece heating is 100^0C.

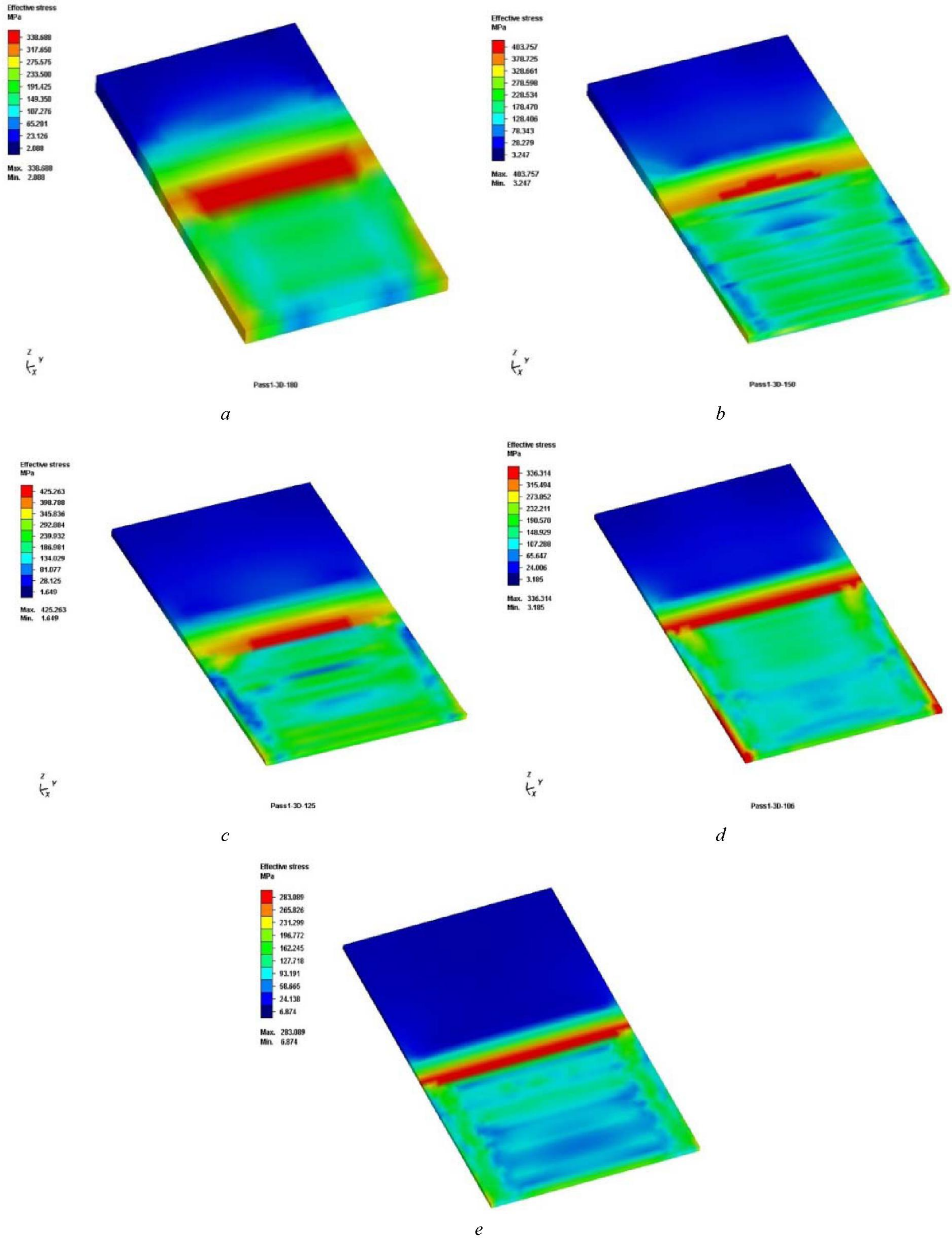


Figure 5 – The pattern of stress intensity distribution in the workpiece during rolling in LWM (rolling temperature 100 °C):
a – 1stand; *b* – 2stand; *c* – 3stand; *d* – 4stand; *e* – 5stand

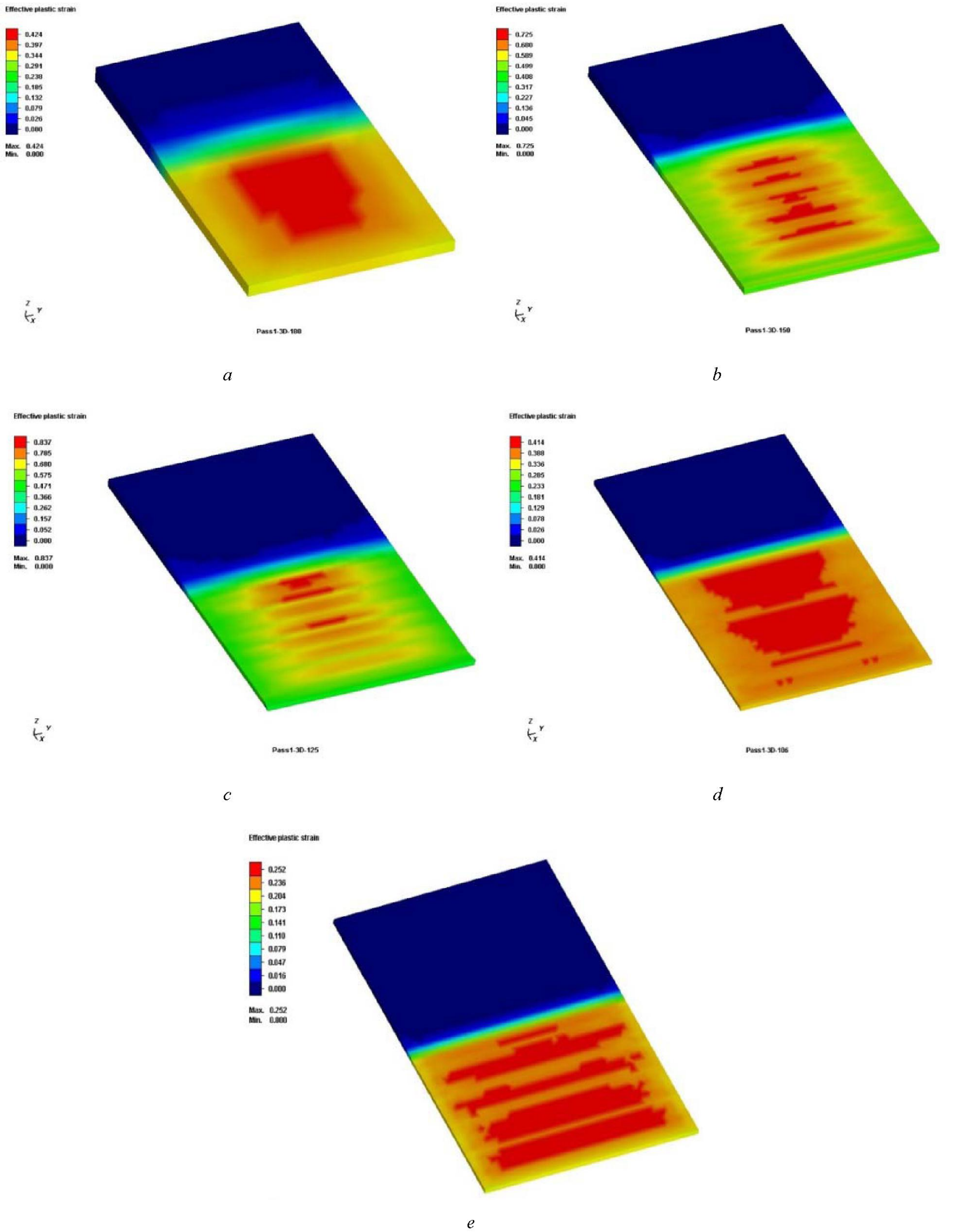


Figure 6 – The pattern of deformationintensity distribution in the workpiece during rolling in LWM (rolling temperature 100 °C):
a – 1stand; *b* – 2stand; *c* – 3stand; *d* – 4stand; *e* – 5stand

Calculation and analysis of the SSSshow that:

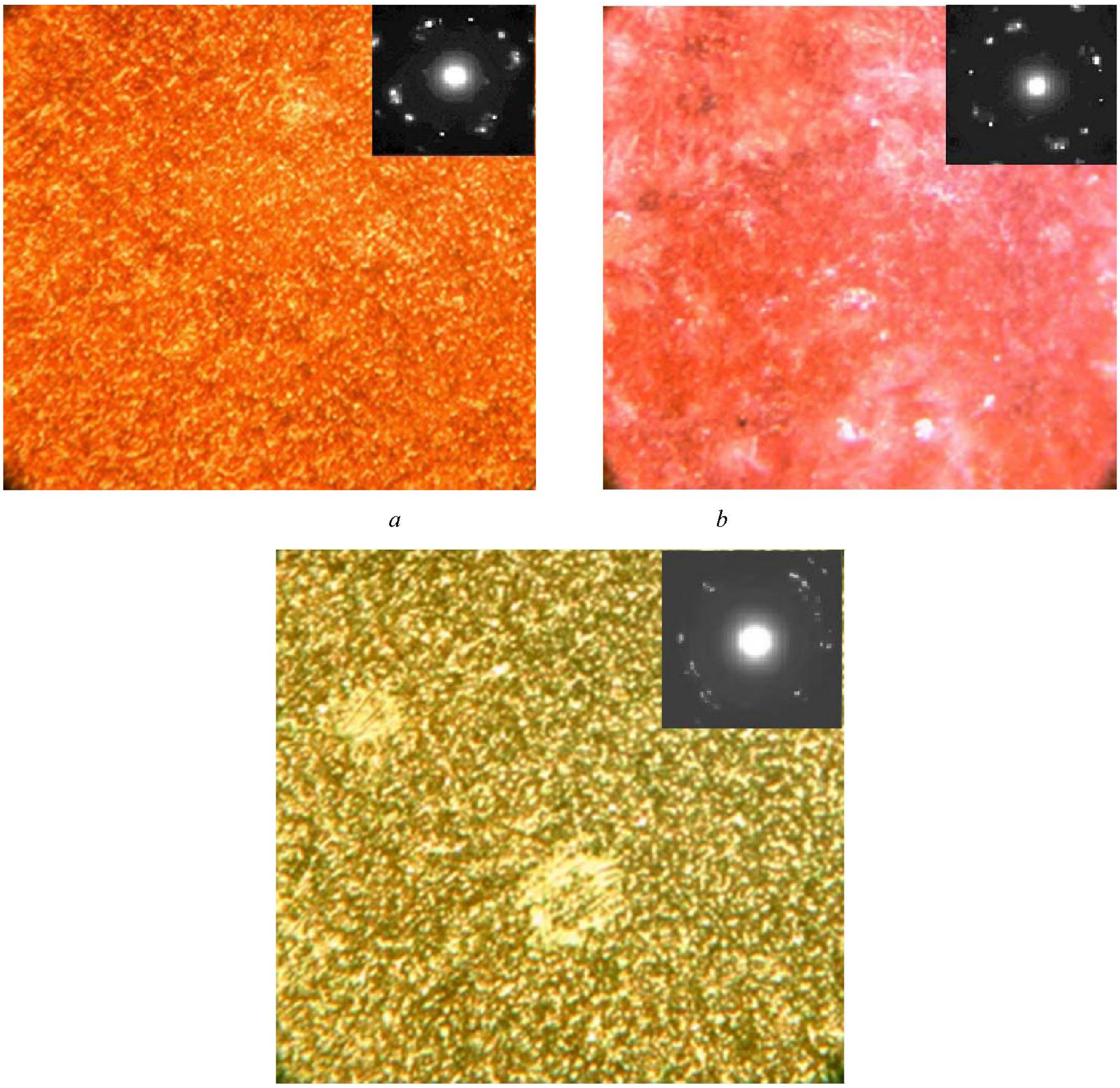
- the capture of the workpiece by the LWM's stands leads to the appearance of minimal tensile stresses σ_{11}, σ_{22} and compressive stress σ_{33} in the deformation zone, and further rolling to the opposite stress states, values ofwhich vary in the range: σ_{11} – from 123,460 to 250,205 MPa; σ_{33} – from - 70,643 to - 150,842 MPa; σ_{22} – from 134,405 to - 11,978 MPa;
- when rolling the workpiece in the first stand of the LWM, the intensities of stresses and deformations are localized in the zones of metal capture by the rollers, and with increasing compression, the values of these parameters increase in the center and along the edges of the deformed workpiece;
- deformation of the billet in the following stands of theLWM allow to gradually concentrate the intensity of stresses and deformations from the surface zone to the central layers of the billet, and then evenly deform the strip along its entire length (figures 5 and 6);
- a uniform distribution of the strain intensity leads to a uniform distribution of the accumulated deformation along the sections of the strip, with the most uniform distribution of the sheardegree deformation along sections of the strip obtained by rolling with a single reduction in the first stand 20%, in the second stand 20%, in the third stand 20%, in the fourth stand 15%, in the fifth stand 10%;
- rolling in the LWM leads to intensive cooling of the strip sections located in the areas of contact of the metal with the roller;
- in the process of rolling blanks from L63 brass in LWM, the maximum value of the stiffness coefficient of the stress state circuit and DPRU occurs along the edges of the strips;
- under any conditions of rolling in the LWM, the major part of the plastic zone is under a comprehensive uneven compression, also under some conditions, insignificant tensile stresses appear on the edges of the bands;
- when rolling strips, made of brass L63 in LWM, the degree of the use of the plasticity resource does not exceed one, which shows the absence of a discontinuity in the continuity of the workpiece material.

Using the obtained results of the SSS distribution along the cross section of the billet during rolling in HR and LWM, a technology for manufacturing strips withUFG structure was developed.

A study of the microstructure showed that in the initial state the preform of brass of L63 has an inhomogeneous coarse-grained microstructure. This structure consists of grains with an average size of ~ 86 μm in the longitudinal and ~ 91 μm in transverse directions.

Investigation of the structural state of the L63 brass after rolling in the HR and LWM showed that:

- after rolling the workpiece by four passes in sections, which are perpendicular and parallel to the rolling plane, grains are formed with a size range from 28 μm to 76 μm;
- rolling the strips by four passes in HR leads to a mixed microstructure consisting of large initial grains with a strip structure and areas with new small grains of ~ 13-19 microns in size with a volume fraction up to ~ 60%;
- the width of the above-noted microbands with large-angle boundaries varies within 23 ± 29 μm at a maximum value of ~ 32 μm, and microbands with small-angle boundaries vary from 12 to 16 μm at the most probable values of about 18 μm;
- further deformation of the billet in HR by eight passes led to the formation in its sections of a crushed, uniform and equiaxed grain-subgrain structure with an average grain size of about 12 to 57 μm, with the formation of large-angle boundaries in the border regions of grains;
- subsequent rolling of the billet in HR leads to the formation of a more uniform structure consisting entirely of crystallites separated by large-angle boundaries, the average size being reduced to 8-37 μm;
- after rolling by twelve passes, there are single grains with a maximum size of 38 μm. The appearance of single relatively large grains can be explained by the passage of therecrystallization processes in the material at a given degree of deformation;
- the microstructure of the L63 brass after rolling by four, eight and twelve passes in the HR and subsequent rolling on the LWM at 100 °C is characterized by the presence of a uniform UFG structure with a grain size of 8-12 μm, 2-6 μm and 640-770 nm, respectively (figure 7);
- on the images of the microstructure after rolling in the HR and LWM, a clear image of the grain boundaries was observed. The type of microstructure indicated the formation of grains with large-angle boundaries;



a *b*

c

Figure7 – The microstructure of the L63 brass after heating and rolling by four (*a*), eight (*b*) and twelve (*c*) passes in the HR and LWM

- when deformed by twelve passes in HR and LWM, the appearance of the UFG structure is clearly determined from the electron diffraction pattern taken from the area of 1.4 μm^2. The electron diffraction patterns for these structures are quasi-circular (figure 7*c*, insert). On the rings, individual reflexes are clearly distinguishable, their distribution along the ring indicates the presence of high-angle misorientations between the fragments. This kind of electron diffraction pattern is typical for ultrafine-grained metal materials obtained by the IPD method and indicates a significant number of elements per unit volume, the presence of large-angle misorientations between them and the presence of elastic stresses in individual elements [5, 6].

According to electron-microscopic images of the structure, the scalar dislocation density, fragment size and misorientation at their boundaries at different grain sizes were measured. It was found that the density of dislocations in a fragmented substructure increases with the number of passes at all grain sizes. The size of fragments with increasing number of passes decreases.

It should be noted that the UFG structure with the above dimensions practically does not contain dislocations in the body of grains. Dislocations are located only on the grain boundaries. The density of dislocations at the grain boundaries is very high, and therefore it was not possible to calculate the magnitude of the dislocations at the grain boundaries.

Metallographic studies have shown that fragmentation of the structure in brass L63 occurs already at the first stages of rolling in HR by sliding and predominantly by twinning. With the increase in the number of passes, further refinement of the microstructure is due to the intersection and crushing of twins, the formation of dislocation subgrains, the dislocation slip, and the gradual increase in misorientation of the subgrains.

It is known [33] that during the plastic deformation of a polycrystal in local sections inside the grains, the deformation can be either plastic or elastic-plastic. Internal stresses are characterized by a stress tensor. Contributions of the stress tensor components, arising during the rollingin HR, to the plastic and elastic components of internal stresses are advantageous. Therefore, by using the methods of metallography, the evolution of the contributions of the components of bending and torsional stresses, which occurs during the rolling in HR, into the plastic component of internal stresses of a deformed copper alloy was investigated.

Many studies have shown that the deformation of steels and alloys is accomplished by two mechanisms of sliding and twinning [33]. Slip occurs at the first stages of plastic deformation. Starting from $\varepsilon \approx 5\%$, fine-scale twining appears. In the range of deformation degrees $\varepsilon = (5 - 10)\%$, there is one system of fine-scale twining. As the degree of deformation increases, so does the number of fine-scale twining systems. Thus, at a degree of deformation $\varepsilon = 10\%$, the second system of fine-scale twinging appears. Starting with a degree of deformation of 25%, the number of fine-scale twinning systems increases to three, and at $\varepsilon = 30\%$ the fourth fine-scale twinning system appears.

It is established that the rolling in the HR the magnitude of the components of the bending and twisting stressesvaries. With increasingdraft, the bending value decreases and the amount of twisting stress increases.This leads to an increaseoffine-scale twisting systems in the material of theworkpiece. Consequently, when rolling in an HR, first the bending stresses σ_{11} increases, which leads to the appearance of the first and second fine-scale twisting systems. This stress leads to an increase in the plastic component of internal stressesσ_{plast}. Further deformation of the workpiece in the HR leads to an increase in the twisting stress σ_{12}. Under the influence of this component of the stress tensor, the plastic component of the internal stresses also increasesσ_{plast}. Under the action of the twisting stress σ_{12}, a third system of fine-scale twining appears in the metal structure. In the subsequent passes, the values of the components σ_{11}, σ_{12} gradually increase in turn, which leads to an increase in the plastic component σ_{plast} over the entire section of the workpiece.

With an increase in the number of rolling passes in HR, the values of the bending stress components and the torsional stress of the crystal lattice in each pass gradually increase or decrease, but the plastic component of the internal stresses and the average stress throughout the material gradually increase. All this leads to the appearance and development of the fourth twinning system

It should be emphasized that during rolling of explosives, an increase or decrease in the components of the bending and torsional stresses of the crystal lattice makes a large contribution to the plastic component of internal stresses, which leads to an increase in the number of sliding systems and fine-scale twining in the process of deformation of brass L63.

Consequently, with the increase of deformation degree in each rolling pass in the HR, the grinding of the structure occurs not only by twinning, but also by the formation of cellular substructures as a result of the development of slip dislocation processes. At large degrees of accumulated deformation, the boundaries of the former twins and subgrainsare transformed into large-angle boundaries.

It is well known [34] that in any crystal the slip and twinning are possible only along certain crystallographic planes determined by the geometry of the structure and in certain directions lying in these planes. Despite a significant number of similar slip systems (or twinning), at each moment of deformation, only one system operates, but different sliding systems can act at different stages of deformation

In the first approximation, it is believed that at first, the deformation proceeds along the system most favorably oriented toward the direction of maximum stress [35]. The plastic shear begins usually along a slip system, where the greatest shear stress acts, and the slip itself occurs at a critical value of the Schmid-stress. According to Schmidt's law, slip begins on one or several surfaces on which the tangential stress has reached a critical value, and the remaining planes are inactive. Then, as a result of the shift, the axes of the crystal are rotated, and a double shift, i.e., can occur. simultaneous sliding in two systems. As the stress increases, the deformation begins along less favorably oriented planes. Consequently, various slip systems successively enter the process of plastic flow, which can be fixed by phenomenological study of the process of metal deformation.

Thus, when rolling in the HR, intergranular and intragranular deformation is facilitated, and a large number of sliding systems are involved in plastic deformation for the following reasons:

- during rolling in the HR, due to the consequent occurrence of the bendingσ_{11} and twisting σ_{12} stresses, the orientations of the favorably oriented to the direction of action of the maximum tangential stresses of the planes change, which leads to dislocation movement in various close-packed slip planes. Consequently, dislocations of all close-packed planes are involved in deformation and motion;
- when rolling in the HR due to the rotation of the deformation center, the ratio between the number of edge and screw dislocations of close-packed planes is well regulated. This makes it possible to form the optimal combination of dislocation components in such a way that at the first moment of rolling the deformation is provided by edge dislocations with a low Peierls barrier, and further development of plastic deformation is occurred by screw dislocations;
- during deformation in the HR at the initial moment of rolling, average by the value compressive stresses arise. It is known [35], that these stresses contribute to the creation of a dislocation structure with predominance of helical orientation. Under the action of large normal compressive stresses on the slip plane, the mobility of screw dislocations decreases. However, in the subsequent stages of rolling in HR, tangential stresses σ_{12} and shear deformations are significant in magnitude. These stresses favorably affect the mobility of the screw components of the dislocations. Since they allow split dislocations to be easier (from the energy point of view) to change the slip plane, if more favorable, from the Schmid law point of view, are blocked. Thus, the use of shear deformation schemes for the rolling in HR ensures, at the initial moment, plastic deformation in the main by the edge dislocations. However, further development of plastic deformation is due to the motion of screw dislocations;
- when rolling in HR, screw dislocations have a greater degree of freedom, changing the plane of their sliding depending on the local stress field in a given region. It should be noted that when rolling in these rolls, the metal is in a complex loading field. Therefore, one of the elements of stress relaxation is the motion of screw dislocations;
- when rolling in the HR, the motion of the screw dislocations allows the metal to dissipate the supplied energy. This means that their movement is one of the mechanisms of energy dissipation. Undoubtedly, only under certain conditions can he make a significant contribution to the process of deformation along with other mechanisms of dissipation (twinning, pore formation, fragmentation, diffusion mass transfer, intragranular slip, grain-boundary slippage, etc.). All this leads to a rapid passage in the deformable metal of softening processes and a rapid grinding of the metal structure[36].

Thus, when rolling in HR, the action of alternating strain mechanisms ensures fragmentation and reorientation of the crystal lattice. In this case, the grinding of grains along the section of the billet with a fairly high probability occurs much earlier than in the conventional metal processing processes. In this case, large-angle boundaries form in the transverse and longitudinal directions of the billet with high density[36].

Tensile tests of the workpieceshowed that sheets of brass of L63 had high mechanical properties at room temperature. The most important feature is the isotropy of strength and sufficiently high ductility (table).

Mechanical properties of brass L63 (at room temperature) after rolling in HR and on LWM

Angle to the axis of extension, deg	$\sigma_{0.2}$, MPa	σ_V, MPa	δ, %
Rolling in HR – LWM – Heat Treatment			
0	620	750	9.8
45	612	740	9.6
90	607	730	9.4
Rolling on the DUO mill – Heat Treatment			
0	490	540	7.6
45	485	530	7.2
90	480	525	6.8

Conclusions.

1. The rolling by the lower left-screw and upper right-screw rollers with opposite projections and depressions leads to the localization of the intensity of deformation:

a) at the initial stage of rolling in the contact zones with the workpiece, and

b) at subsequent stages - in the zones under the inclined sections of the protrusions and hollows of the rolls.

2. The concentration of the intensity of deformations in the contact zones and under the inclined sections of the protrusions and valleys of the rolls facilitates the selection of rational deformation modes of rolling to obtain strips with a UFG structure.

3. It is shown that a two-step deformation consisting of rolling in the HR and LWM ensures the formation of a homogeneous UFG structure in brass L63 with an average size of 640 to 770 nm, which will lead to an increase in strength and plastic bands.

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БҰРАНДАЛЫ ПІШІНБІЛІКТЕРДЕ ЖӘНЕ БОЙЛЫҚ-СЫНАЛЫ ОРНАҚТА ЖОЛАҚТАРДЫ ЖАЙМАЛАҒАНДА ҚҰРЫЛЫМНЫҢ ҚАЛЫПТАСУ ЕРЕКШЕЛІКТЕРІ

Аннотация. Мақалада қаңылтырлы жаймада ультраұсақтүйіршікті құрылымды алудың жаңа технологиясы ұсынылған. Ультраұсақтүйіршікті құрылым, бұрандалы пішінбілікпен дамытылатын қарқынды пластикалық деформацияны қолдану жолымен алынған. Жұмыста бұрандалы пішінбілік пен бойлық-сынала орнақта дайындаманы жаймалағанда, ода пайда болатын кернеулі-деформациялы күй (КДК) зертелді. Бұрандалы пішінбілікте әртүрлі өтіммен және бойлық-сыналы орнақта дайындаманы жаймалағанда пайда болатын КДК мен температураның сандық мәндері жәнетарқалуының негізгі заңдылықтары, шеткі элемент әдістемесімен және «ANSYS-LS/DYNA» және «MSC.SuperForge» бағдарламасымен анықталды. Мақалада Л63 жезін жаймалаудың ұтымды технологиясы жасалып, зертханалық жағдайда тексерілген. Бұрандалы пішінбілік пен бойлық-сыналы орнақта Л63 жезін жаймалағанда, ультраұсақтүйіршікті құрылымының қалыптасуына қаншалықты илемдеу режімі әсер ететіндігі жұмыста талданып, талдау нәтежесіне ерекше көңіл бөлінген. Бұрандалы пішінбілік пен бойлық-сыналы орнақта Л63 жезін жаймалау, қаңылтырлы жайма металының беріктік пен илемділік қасиеін жоғарлатуға алып келетіндігі мақалада табылды.

Түйін сөздер: жез Л63, ультраұсақтүйіршікті құрылым, жаймалау, кернеулі-деформациялы күй, сандық модельдеу, кернеу мен деформация қарқындылығы, беріктік, илемділік.

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ОСОБЕННОСТИ ФОРМИРОВАНИЕ СТРУКТУР ПРИ ПРОКАТКЕ ПОЛОС В ВИНТООБРАЗНЫХ ВАЛКАХ И ПРОДОЛЬНО-КЛИНОВОМ СТАНЕ

Аннотация. В настоящей статье представлена новая технология получение листового проката с ультрамелкозернистой структурой. Ультрамелкозернистая структура получена путем применение интенсивной пластической деформации, развиваемой винтообразным валком. В работе исследовано напряженно-деформированное состояние (НДС) заготовки при прокатке в винтообразных валках и продольно-клиновом стане.

Методом конечных элементов и программами ANSYS-LS/DYNA и «MSC.SuperForge» получены количественные данные и установлены основные закономерности распределения НДС, температуры при прокатке заготовок в винтообразных валках с различным количеством прохода и на продольно-клиновом стане. Разработана и в лабораторных условиях опробовано рациональная технология прокатки латуни Л63. Особое внимание уделено анализу влияния режимов прокатки в винтообразных валках и продольно-клиновом стане на формирование ультрамелкозернистой структуры в латуни Л63. Установлено, что прокатка в винтообразных валках и продольно-клиновом станелатуни Л63 приводит к увеличению прочностных и пластических свойств металла листового проката.

Ключевые слова: латунь Л63, ультрамелкозернистая структура, прокатка, напряженно-деформированное состояние, численное моделирование, интенсивность напряжений и деформаций, прочность, пластичность.

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